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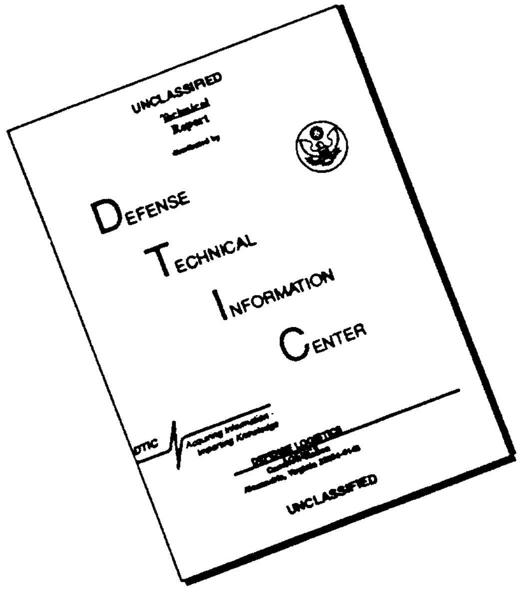

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TECHNIQUES FOR THE MEASUREMENT OF THE FLEXURAL RIGIDITY OF THIN FILMS AND LAMINATES*

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SUMMARY

A method of measuring the flexural rigidity of thin films and laminates is described. The method employs the principle of the heavy elastica which relates flexural rigidity to the deflection of the material under its own weight. Results are presented of tests to determine the stiffness of plastic films and plastic-metal laminates for use in space structures experiments. Tests were performed on untreated and aluminized poly[ethylene terephthalate] film, aluminum foil, and laminates of aluminum foil and poly[ethylene terephtahlate] film or polypropylene film. The thickness of the materials ranged from 0.00018 inch (0.00046 cm) to 0.00270 inch (0.00691 cm). The weight efficiency in flexure is presented, the efficiency of the aluminized poly[ethylene terephthalate] film (Echo I material) being taken as unity.

It has been shown that the principle of the heavy elastica (including both the heart-loop and the cantilever methods) is valid for such determinations if the material does not have a static electric charge. Although higher stiffness can be obtained at the expense of more weight, the investigation showed that the rigidity can increase more rapidly than the weight. Compared with the Echo I material, the laminates had the highest efficiencies of the materials that were tested. A comparison between the flexural stiffness determined by a standard stiffness tester and that determined by the heavy-elastica method revealed that the results of the two methods correlated well only for comparatively large values of stiffness. For small values, however, or for small differences in stiffness, the elastica method was the more sensitive method.

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INTRODUCTION

In structural engineering problems which involve internally pressurized thin shells, it is often assumed, for purposes of simplification, that the shell wall is a membrane which can carry only tension loads and offers no resistance to compression or bending loads. However, thin shells do have some direct and flexural stiffnesses. It has been necessary to utilize these stiffnesses in several space structures experiments, such as the 135-foot-diameter (41.1-m) Echo II passive-communications satellite and the 12-foot-diameter (3.6-m) air-density satellites. The flexural rigidity of single materials can be calculated if the Young's modulus and the thickness of the material is known. In the case of composite materials, especially thin laminates in which the material properties are not well defined, it is usually more realistic to take measurements of the flexural rigidity.

The inherent problems in determining the flexural stiffness of thin, flexible materials are those of accurately measuring very small loads and large deflections. Some methods of determining the stiffness involve the application of a fixed load or deflection and the measurement of the resulting deflection or load. Several instruments and techniques of measuring flexural stiffness are found in references 1 to 11. Another method makes use of the principle of the heavy elastica in which the material deflects under its own weight, the resulting deflection being a measure of the stiffness. (See refs. 12 to 17.)

This report will describe the application of the heavy-elastica principle to some thin films and laminates and the results of measurements of the flexural stiffness of these materials. In addition, a comparison between stiffness measurements obtained by the elastica method and those obtained with a commercial stiffness tester, as well as the weight efficiency in flexure, will be presented. Methods of test for the flexural rigidity of thin films and laminates are given in an appendix by M. David Burt.

SYMBOLS

The units used for the physical quantities in this paper are given both in the U.S. customary units and in the International System of Units (SI). Factors relating the two systems are given in reference 18.

b	width, in. (cm)
c	bending length, defined as $\left(\frac{Ebt^3}{12w}\right)^{1/3}$, in. (cm)
D	flexural rigidity, wc^3, lbf-in^2 (N-m^2)

E	Young's modulus, $\mathrm{lbf/in^2}$ $(\mathrm{N/m^2})$
I	area moment of inertia, defined as $\frac{bt^3}{12}$, $\mathrm{in^4}$ $(\mathrm{cm^4})$
l	length, in. (cm)
t	thickness, in. (cm)
w	weight per unit length, Wb, lbf/in. (N/m)
W	weight per unit area, $\mathrm{lbf/in^2}$ $(\mathrm{N/m^2})$
y	deflection, in. (cm)
μ	Poisson's ratio
θ	deflection angle, deg

Subscripts:

calc	calculated
exp	experimental

DESCRIPTION OF MATERIALS

A description of the materials used in this investigation is given in table I and the composition of the materials is illustrated in figure 1. The tests were performed on two single materials, one composite material, and four laminates. The nominal thickness of each material differs from that measured by an electrically driven micrometer.

The two single materials are aluminum foil and poly[ethylene terephthalate] film (designated PET film herein). The aluminum foil is the high-purity alloy 1080 which was used in the Echo II laminate.

The composite material is the aluminized PET film used in the Echo I passive-communications satellite. The 2200-Å-thick (2.2×10^{-7}-m) vapor-deposited aluminum coating on one side provides a reflecting surface for radio waves and also serves to reduce the ultraviolet degradation of the PET film. (See ref. 19.) The aluminum constitutes approximately 2 percent of the total thickness of the film so that the aluminum thickness shown in figure 1 is not to scale.

The four laminates that were investigated are that used in the Explorer IX air-density satellite (ref. 20), that used in the Echo II passive-communications satellite (ref. 21), and two experimental laminates designated A/M/A and X-32B in reference 22. The X-32B laminate represents an attempt to obtain an unusually lightweight, yet flexurally stiff, material which can be deployed as an expandable structure. The plies of all the laminates are cemented together with an isocyanate-modified polyester adhesive.

DESCRIPTION OF TESTS AND DATA ANALYSIS

The flexural stiffness properties of the materials described in the previous section were determined by both the heart-loop and the cantilever methods. Both methods are based on the heavy-elastica principle. The test procedure is described in the appendix and the test apparatus is shown in figures 2 to 4.

In the heart-loop method, a strip material of known length is formed into a heart-shaped loop and the distance from the top to the bottom of the loop is measured (fig. 3). In the cantilever test the length of the overhang of the specimen and the angle of deflection of the free end below the horizontal (fig. 4(a)) are measured. A specialized form of the cantilever test is performed by allowing the test specimen to deflect to a fixed angle of 41.5° (fig. 4(b)) and measuring only the length of the overhang.

Stiffness tests were also performed on a commercially available stiffness tester that measures the load required to force the material through a slot of a given width (ref. 5). In this test, a 6-inch-square (15.2-cm) piece of the material is centered over a 5-millimeter slot. A 6-inch-wide (15.2-cm) penetrator arm engages the material and drives it through the slot. The resulting force on the penetrator arm is sensed by means of a load cell and displayed on a microammeter that is calibrated in grams. Inasmuch as it was designed to be used in the fabric industry, the instrument measures both stiffness and surface friction. Therefore, the apparent stiffness measurements may not represent the true flexural stiffness of the material.

The Young's modulus and extensional stiffness of the materials were measured on a tensile tester of the type described in reference 23. Strips of the material, of the same width as that being used for the stiffness tests, were secured in grips located 5 inches (12.7 cm) apart. The machine crosshead then was deflected at a rate of 2 and 0.2 inches per minute (0.846 and 0.0846 mm/sec), thus producing a strain rate of 0.4 inch per inch per minute (0.0067 cm/cm/sec) for the PET film and 0.04 inch per inch per minute (0.0007 cm/cm/sec) for the aluminum foil and the laminates.

The calculation of the flexural rigidity from the test data depends upon the test method which is employed. Table II presents a summary of the steps by which the test data may be used to calculate the flexural rigidity. In the heart-loop test (fig. 3) the

deflection of the loop is measured and the ratio of the deflection of one-half the loop length is calculated. By means of the ratio $y/0.5l$ and the curve in figure 5(a), which is taken from reference 15, the ratio $0.5l/c$, where c is referred to as the bending length (ref. 12), is determined. The flexural rigidity then is simply wc^3 where w is the weight of the strip per unit length. In reducing the data from the variable-angle cantilever tests, the ratio c/l is determined from the curve in figure 5(b), which is taken from reference 15. Because the angle θ was measured in $1/2^o$ increments, a table of values (table III) of θ and c/l was constructed from figure 5(b) to aid in the calculation of the flexural rigidity. Once the value of c/l is obtained, from either figure 5(b) or table III, the flexural rigidity wc^3 can be calculated.

When the fixed-angle stiffness tester (fig. 4(b)) recommended in reference 17 is used, only the length of the overhanging strip is measured. Because the angle is 41.5^o, the bending length c is exactly one-half the length of the overhang. Again the flexural rigidity is wc^3.

RESULTS AND DISCUSSION

The results of the flexural stiffness tests are listed in tables IV to IX and illustrated in figures 6 to 9. Unless otherwise indicated, each value of flexural rigidity is the arithmetic mean of 23 to 27 tests, and one standard deviation follows the ± sign.

PET Film and Aluminum Foil

The flexural stiffness properties of 0.00035- and 0.001-inch-thick (0.00089- and 0.0025-cm) PET film and 0.00018-inch-thick (0.00046-cm) aluminum foil are listed in table IV and illustrated in figure 6 where the values have been normalized to unit width. The advantage of testing these single materials is that the flexural stiffness can be more easily calculated and compared with the measured values. The Young's modulus was determined for each area of film and foil that was tested along the roll of the material. The flexural rigidity (ref. 24) was calculated from

$$D = \frac{EI}{1 - \mu^2} = \frac{Ebt^3}{12(1 - \mu^2)}$$

Poisson's ratio μ was taken as 0.33 for the aluminum foil and, in the absence of an established value, 0.5 for the PET film. Although Poisson's ratio for the highly crystalline film is undoubtedly less, a value of 0.5 would give the highest value of flexural rigidity and the most conservative comparison between experimental and calculated rigidity. The plate rigidity D was used instead of the beam stiffness $B = EI$ that is given in reference 15, because the films and laminates are plate configurations (width-to-thickness ratios ranging from 220 to 5000). The substitution of D for B, however,

does not invalidate the derivation in reference 15. As has been reported previously (ref. 21), the values of Young's modulus for the aluminum foil as determined by tensile tests seemed to be unreasonably low (table IV). Therefore, the accepted value of Young's modulus of 10^7 lbf/in^2 (6.9×10^{10} N/m^2) was used in the calculations for the aluminum foil.

A comparison between the measured and the calculated rigidity of the PET film and the aluminum foil is shown in figure 6 where logarithmic axes are used to accommodate the wide range of values. It can be seen that the measured rigidity of the PET film and aluminum foil is generally lower than the calculated plate rigidity.

In the heart-loop tests of the PET film there was a length dependence (table IV) that was more apparent than real. The PET film can acquire a static electric charge during the normal preparations for a test. The charge tends to collapse the film loop and so increase the measured loop deflection. The indicated rigidity of the film, then, is lower than it would be without the charge. For this reason the results of the PET film are conservative. (For 0.00015-inch-thick (0.000381-cm) PET film, heart-loop tests were impossible to perform because the static charge caused complete collapse of the loop.)

The flexural rigidity of the 0.00035-inch-thick (0.00089-cm) PET film determined by the cantilever method was as high or higher than the rigidity obtained with the heart-loop tests. The effect of the static charge is negligible in the cantilever test and the strip length is variable, unlike the strip length in the heart-loop test. The length varied from 0.52 to 1.27 inches (1.32 to 3.22 cm) with 0.90 to 1.00 inch (2.29 to 2.54 cm) being typical values. Using the calculated rigidity as a basis for comparison, then, it appears that the cantilever test gives more reliable results for the PET film than does the heart-loop test. The cantilever test will work equally well for other polymer films which may be subject to a static electric charge.

Heart-loop tests were not performed on the aluminum foil inasmuch as this method is useful primarily for materials of lower modulus. The cantilever tests, however, provide reasonable values of stiffness except for the fixed-angle ($\theta = 41.5^\circ$) tests of the 0.5-inch-wide (1.27-cm) strips. There is no apparent reason for the low values obtained in these tests, but, assuming that the other aluminum tests are valid, an experimental error or material defect probably influenced the test results. It is concluded, then, that both the heart-loop method and the cantilever method provide rigidity values that are within approximately 20 percent of the calculated values if there are no effects due to a static electric charge.

Echo I Material

The results of the flexural rigidity tests of the Echo I material are listed in table V and shown in figure 7. Although the film behaves mechanically like a two-layer laminate

(ref. 22), the calculated rigidity values in table V are based on the assumption that the film is a single material. Such an assumption is reasonable, however, inasmuch as the actual thickness of the vapor-deposited aluminum is not known (the thickness may range from the nominal 2200 Å (2.2×10^{-7} m) down to 1500 Å (1.5×10^{-7}m)), and Young's modulus for vapor-deposited aluminum is not well established. However, tests were performed with the aluminized side in compression and were repeated with the aluminized side in tension, in order to determine the effect of the static electric charge.

The test results of figure 7 fall into one group when they are normalized to unit width, except for the fixed-angle cantilever tests that were performed with the aluminized side in compression. In this position the aluminum made electrical contact with the steel parts of the apparatus (fig. 4(b)), and the static electric charge set up a repulsive force between the film and the apparatus. Thus, the film did not deflect as much as it would have without the charge and, as a result, the measured rigidity was higher. When the aluminized side of the film was in tension, a wooden indicator weight prevented electrical contact between the aluminum and the apparatus. Consequently, no repulsive force developed and the measured rigidity was comparable to that obtained from the variable-angle and the heart-loop tests. The static charge affected the measured rigidity of the Echo I film determined by the heart-loop tests as in the case of the PET film. There appeared to be no effect, other than the static charge, of having the aluminized side of the film in tension or in compression. In general, then, both test methods are applicable to the Echo I material and provide rigidity values that are within less than 20 percent of the calculated values except where the static electric charge would influence the test results.

Spacecraft Laminates

Table VI lists the flexural rigidity of some laminates that have been used or proposed for use in expandable spacecraft and satellites. It is possible to calculate the rigidity of the laminates (ref. 25) if the Young's modulus and the thickness of the components are known. In addition, it must be assumed that there is a good bond between the laminate plies. Since some doubt exists regarding the thickness of the materials (compare nominal and measured thicknesses in table I) and since the behavior of the adhesive in shear is not well known, it is more realistic to measure the flexural rigidity than to calculate it. The rigidity was measured by means of the fixed-angle and variable-angle cantilever tests, because the heart-loop test is impractical for the comparatively thick and stiff laminates.

The tests of the Explorer IX and A/M/A laminates were made on only the variable-angle cantilever apparatus because the comparatively high rigidity of the laminates prevented them from deflecting to 41.5° for any reasonable strip length. The flexural rigidity is comparable for the two laminates (2.28×10^{-3} lbf-in^{2} (6.54×10^{-6} N-m^{2}) for the

Explorer IX laminate compared with 2.50×10^{-3} lbf-in^2 (7.17×10^{-6} N-m^2) for the A/M/A laminate) as is the unit weight. The standard deviation, however, of the data for the A/M/A laminate (1.06×10^{-3} lbf-in^2 (3.04×10^{-6} N-m^2)) is over twice that for the Explorer IX laminate (0.47×10^{-3} lbf-in^2 (1.35×10^{-6} N-m^2)). The implication, then, is that the four-layer Explorer IX laminate has more consistent flexural properties than does the three-layer A/M/A laminate.

The Echo II laminate had fairly consistent flexural properties when it was tested by means of the fixed-angle cantilever apparatus, a value of 1.41×10^{-4} lbf-in^2 (4.04×10^{-7} N-m^2) being obtained for a 0.5-inch-wide (1.27-cm) strip. With the variable-angle apparatus, however, a high value of 2.92×10^{-4} lbf-in^2 (8.38×10^{-7} N-m^2) for a 0.5-inch-wide (1.27-cm) strip was measured. For the fixed-angle cantilever apparatus the X-32B laminate had a flexural rigidity that was nearly the same as that of Echo II. Both laminates had a rigidity that was comparable to that of 0.0007-inch-thick (0.0018-cm) general-purpose aluminum foil, approximately 3.2×10^{-4} lbf-in^2 (9.18×10^{-7} N-m^2) per unit width.

The rigidity values obtained with the variable-angle apparatus are approximately 10 to 100 percent higher than those obtained with the fixed-angle tester for a given material and strip width. (See tables IV and V.) Such differences could be caused by varying rigidity of different areas of a material, by the different apparatus, or by the slight difference in test technique. (See the appendix.) For example, in the fixed-angle technique the test specimen is slid along the top of the pylon until the free end deflects to 41.5°. By contrast, in the variable-angle technique one end of the specimen is placed on the pylon, a weight is placed on the specimen, and then the specimen is allowed to deflect to any angle up to 55°. Therefore, 0.5-inch-wide (1.27-cm) strips of the Echo II laminate were cut from the same general area of the roll of material in order to minimize any variation in results due to varying rigidity, and both techniques were investigated on each apparatus.

The flexural rigidity of 0.5-inch-wide (1.27-cm) strips of the Echo II laminate is given in table VII. When the fixed-angle technique and apparatus were used, a value of 1.89×10^{-4} lbf-in^2 (5.42×10^{-7} N-m^2) was obtained. A similar value of 1.93×10^{-4} lbf-in^2 (5.54×10^{-7} N-m^2) was obtained when the fixed-angle technique was used with the variable-angle apparatus. In other words, there is less than a 2-percent difference in the results of the different apparatus. The variable-angle technique and apparatus, however, yielded a value of 2.16×10^{-4} lbf-in^2 (6.20×10^{-7} N-m^2) and the same technique with the fixed-angle apparatus gave a value of 2.20×10^{-4} lbf-in^2 (6.31×10^{-7} N-m^2). Again, there is less than a 2-percent difference in the values obtained with the different apparatus. The variable-angle technique, however, yielded values that are 10 to 15 percent higher than those obtained with the fixed-angle technique. In addition, the value listed in table VII for the fixed-angle apparatus and technique is

approximately 30 percent higher than that listed in table VI. It appears, then, that the slight difference in test technique, combined with the variation in material properties for the same laminate, can lead to a wide range of flexural rigidity values for a given material.

Weight Efficiency

Increased rigidity may not be desirable in spacecraft materials depending upon how much extra weight is required to obtain the extra stiffness. Therefore, the weight efficiency in flexure was calculated for each material by dividing the representative values of the rigidity of a 1-inch-wide (2.5-cm) strip by the weight per unit area. The weight efficiency relative to the Echo I material was calculated and the results are listed in table VIII and plotted in figure 8. The rigidity of the Echo I material was used as a basis for comparison because the laminates were designed to be flexible yet stiffer than it.

The highest weight efficiencies (141 times that of the Echo I material) are those of the Explorer IX and A/M/A laminates which weigh approximately 7 times as much as the Echo I material. However, the laminates should be useful in cases in which a small (and, therefore, low total weight) but relatively stiff structure is required. Such size and rigidity requirements were in fact encountered in the Explorer IX air-density satellite (ref. 20).

The Echo II and the X-32B laminates have weight efficiencies that are 25 and 28 times that of the Echo I material. The X-32B laminate may be more efficient in orbit than is indicated in table VIII and figure 8 because the material weight is the deforming load in the flexural rigidity tests, whereas solar pressure, not gravity, is the major deforming load in orbit. The polypropylene windows (see fig. 1) contribute to the deforming load in a stiffness test, but in orbit the sunlight would be transmitted through the windows and would thereby reduce the deforming load on the structure. The X-32B laminate, therefore, may be more efficient than the flexural rigidity tests indicate.

Rigidity Measured by Stiffness Tester

A variety of commercially available stiffness testers are available (refs. 9 to 11) which are used to determine the stiffness of materials such as plastic films, metal foil, paper, fabrics, and leather. Such testers generally do not have the range or sensitivity required to determine the flexural rigidity of the materials in this investigation. However, the data obtained by the heart-loop and cantilever tests were compared with the results obtained with a stiffness tester, the values from which have been shown to correlate well with the dynamic modulus of plastic films (ref. 5). The tester employs a thin wedge to push a sample of the material through a slot of a given width. The force

required to deform the material in this manner is taken as a measure of both the stiffness and frictional qualities of the material.

The flexural rigidity as determined by the elastica method and the deflection force measured on the stiffness tester are listed in table IX and shown in figure 9. The deflection force is about the same for the 0.00035-inch-thick (0.00089-cm) PET film, the 0.00018-inch-thick (0.00046-cm) aluminum foil, and the Echo I material, even though the flexural rigidity differs by a factor of 1.5 to 4. Over a range of several orders of magnitude of rigidity, however, there is a reasonable correlation between deflection force and stiffness, and for large values of stiffness the results of the two methods correlated well. Any correlation is remarkable inasmuch as the materials that were investigated represent a wide range of stiffness and frictional characteristics and as the stiffness tester was not designed to test metal-surfaced materials.

CONCLUDING REMARKS

Techniques for determining the flexural rigidity of several thin films and laminates for expandable space structures have been evaluated. It has been shown that the principle of the heavy elastica (including both the heart-loop and the cantilever methods) is valid for such determinations if the material does not have a static electric charge. Although higher stiffness can be obtained at the expense of more weight, the investigation showed that the rigidity can increase more rapidly than the weight. Compared with the Echo I material, the laminates had the highest efficiencies of the materials that were tested. A comparison between the flexural stiffness determined by a standard stiffness tester and that determined by the heavy-elastica method revealed that the results of the two methods correlated well only for comparatively large values of stiffness. For small values, however, or for small differences in stiffness, the elastica method was the more sensitive method.

Langley Research Center,
National Aeronautical and Space Administration,
Langley Station, Hampton, Va., October 22, 1965.

APPENDIX

METHODS OF TEST FOR THE FLEXURAL RIGIDITY OF THIN FILMS AND LAMINATES

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The specimens for the flexural rigidity tests were prepared by one of three methods, depending on the nature of the material. The polymer films were cut on the drum cutter which is shown in figure 2(a). Strips of film can be cut in widths from 0.5 to 8 inches (1.27 to 20.3 cm) in 0.5-inch (1.27-cm) increments. As shown in figure 2(a), the cutter is set to cut 1-inch-wide (2.5-cm) strips. The laminates and aluminum foil were not cut on the drum cutter because wrapping the laminate around the drum introduced a curvature in the specimen which influenced the results. Therefore, 0.5-inch-wide (1.27-cm) strips of the laminates were cut on the shear cutter shown in figure 2(b). Only one specimen at a time can be produced satisfactorily by this cutter. For laminate-specimen widths of 1 inch (2.5 cm) it was necessary to cut the specimens by hand with use of a razor blade and a straight edge.

The apparatus for the heart-loop method is shown in figure 3. A strip of the material to be tested is laid across two gage marks on a guide board. The distance between the marks is l and the free ends of the strips extend beyond them. Two strips of cardboard, about 0.5×2 inches (1.27×5.1 cm), are laid on top of the specimen so that the inner edges of the strips are coincident with the gage marks. Cellophane tape is used to fasten the strips and the free ends of the specimen. The strips then are given a three-quarter turn and brought together so that the specimen forms a loop with the free ends passing down between the cardboard strips. It was convenient to use tweezers to hold the strips together and to position the loop as shown in figure 3. A windshield was then placed around the stand holding the loop. Measurements of the distance between the top and the bottom of the loop were made to the nearest 0.01 cm with a cathetometer. In the cases in which the two upper curves of the heart loop were at slightly different heights, measurements were made of the height of each curve and the average value was used to determine the distance between the upper and lower curves of the loop.

The instruments for the cantilever tests are shown in figure 4. When the variable-angle apparatus in figure 4(a) is used, the specimen is supported and extended from the pylon for a distance varying from 1 to 5 inches (2.5 to 12.7 cm), depending upon the stiffness of the material. A weight then is placed on the sample at the edge of the pylon to

insure that there is no angular rotation of the root of the cantilever. The specimen is allowed to deflect and the angle of deflection is measured to the nearest $1/2^{\circ}$ on the protractor. The sample is marked with a line at the edge of the pylon and then is drawn back a short distance. The weight is then replaced, the deflection angle is recorded, and the sample is marked once again. After two or three readings are made, the sample is removed from the tester and the length of the overhang is measured to the nearest 0.01 inch (0.025 cm). The distance of the previously mentioned marks from the free end of the sample is a measure of the overhang.

When the fixed-angle tester is used (fig. 4(b)), the sample is placed flat on the pylon so that the free end coincides with the front edge of the pylon. The indicator weight is placed on the sample so that its end coincides with the end of the pylon and test sample. The indicator weight and the sample are then slid along the top of the pylon until the free end of the sample deflects to 41.5° below the horizontal. The angle is indicated by two fixed wires between which the sample can pass. The extended length of the sample is read directly on the scale on top of the pylon to the nearest 0.01 inch (0.025 cm).

The stiffness tester and procedure which are described for the fixed-angle-cantilever and heart-loop methods follow closely the recommendations that are given in reference 17.

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TABLE I.- DESCRIPTION OF MATERIALS

Material	Nominal thickness		Measured thickness		Weight per unit area, W		Composition
	in.	cm	in.	cm	lbf/in^2	N/m^2	
PET film	0.00035	0.00089	0.00031	0.00079	1.75×10^{-5}	1.21×10^{-1}	Poly[ethylene terephthalate], capicator grade, biaxially oriented.
	.001	.00254	.00098	.00249	4.79×10^{-5}	3.30×10^{-1}	
Aluminum foil	0.00018	0.00046	0.0002	0.00051	1.93×10^{-5}	1.33×10^{-1}	Alloy 1080.
Echo I material	0.0005	0.00127	0.00042	0.00107	2.45×10^{-5}	1.69×10^{-1}	0.5-mil PET film with 2200-Å-thick (2.2×10^{-7} m) vapor-deposited aluminum on one side.
Explorer IX laminate	0.002	0.00508	0.00225	0.00571	1.64×10^{-4}	1.13	Four-ply laminate of 0.5-mil (0.00127 cm) PET film and 0.5-mil (0.00127 cm) aluminum foil cemented with polyester adhesive.
Echo II laminate	0.00071	0.00180	0.0008	0.00203	5.70×10^{-5}	3.93×10^{-1}	Three-ply laminate of 0.35-mil (0.00089 cm) PET film cemented between 0.18-mil (0.00046 cm) aluminum foil with polyester adhesive.
X-32B laminate	0.00096	0.00244	0.0011	0.00279	3.82×10^{-5}	2.63×10^{-1}	Three-ply laminate of 0.6-mil (0.00152 cm) polypropylene film cemented between 0.18-mil (0.00046 cm) aluminum foil with polyester adhesive; 58% of aluminum removed in hexagonal pattern by chemical milling.
A/M/A	0.00270	0.00686	0.00285	0.00724	1.77×10^{-4}	1.22	Three-ply laminate of 2-mil (0.00508 cm) PET film cemented between 0.35-mil (0.00089 cm) aluminum foil with polyester adhesive.

TABLE II.- PROCEDURES FOR MEASURING THE FLEXURAL RIGIDITY OF THIN MATERIALS

Method	Measurable quantities			Data reduction			
	Strip length, l	Strip width, b	Strip deflection, y	Ratio of deflection to strip length	Ratio of strip length to bending length	Bending length, c	Flexural rigidity, D, wc^3
Heart loop	Fixed	Fixed	Measured	$y/0.5l$ calculated	$0.5l/c$ value from curve	Calculated from $y/0.5l$ and $0.5l/c$	Calculated
Cantilever, $\theta = 41.5^{\circ}$	Measured	Fixed	Fixed	$\tan^{-1}\theta$	$c/l = 0.5$	$0.5l$	Calculated
Cantilever, θ variable	Measured	Fixed	Measured	$\tan^{-1}\theta$	c/l value from curve	Calculated from from l and c/l	Calculated

TABLE III.- RELATIONSHIP BETWEEN DEFLECTION ANGLE AND THE RATIO OF THE BENDING LENGTH TO THE OVERHANG LENGTH IN THE CANTILEVER TESTS

Deflection angle, θ, deg	c/l	Deflection angle, θ, deg	c/l	Deflection angle, θ, deg	c/l
10.0	0.887	30.0	0.589	50.0	0.441
10.5	.872	30.5	.584	50.5	.437
11.0	.856	31.0	.580	51.0	.434
11.5	.843	31.5	.575	51.5	.431
12.0	.833	32.0	.571	52.0	.428
12.5	.822	32.5	.567	52.5	.425
13.0	.811	33.0	.563	53.0	.422
13.5	.800	33.5	.558	53.5	.419
14.0	.789	34.0	.554	54.0	.416
14.5	.781	34.5	.550	54.5	.413
15.0	.772	35.0	.546	55.0	.410
15.5	.763	35.5	.542	55.5	.408
16.0	.754	36.0	.538		
16.5	.746	36.5	.534		
17.0	.738	37.0	.530		
17.5	.731	37.5	.527		
18.0	.722	38.0	.524		
18.5	.716	38.5	.521		
19.0	.708	39.0	.518		
19.5	.702	39.5	.514		
20.0	.696	40.0	.511		
20.5	.689	40.5	.508		
21.0	.684	41.0	.504		
21.5	.677	41.5	.500		
22.0	.671	42.0	.496		
22.5	.665	42.5	.492		
23.0	.658	43.0	.489		
23.5	.654	43.5	.485		
24.0	.648	44.0	.482		
24.5	.642	44.5	.479		
25.0	.638	45.0	.476		
25.5	.632	45.5	.473		
26.0	.627	46.0	.469		
26.5	.623	46.5	.466		
27.0	.617	47.0	.462		
27.5	.613	47.5	.458		
28.0	.607	48.0	.455		
28.5	.603	48.5	.451		
29.0	.598	49.0	.448		
29.5	.594	49.5	.444		

TABLE IV.- FLEXURAL RIGIDITY OF PET FILM AND ALUMINUM FOIL

Nominal thickness, t		Test method	Strip width, b		Weight of strip per unit length, w		Strip length, l		Young's modulus, E		Flexural rigidity, D			
											Calculated		Measured	
in.	cm		in.	cm	lbf/in.	N/m	in.	cm	lbf/in^2	N/m^2	$lbf\text{-}in^2$	$N\text{-}m^2$	$lbf\text{-}in^2$	$N\text{-}m^2$
PET film														
0.00035	0.00089	Heart loop	0.5	1.27	0.875×10^{-5}	1.53×10^{-3}	3	7.62	5.78×10^{5}	3.99×10^{9}	9.56×10^{-7}	2.74×10^{-9}	$(6.39 \pm 0.54) \times 10^{-7}$	$(1.83 \pm 0.15) \times 10^{-9}$
							4	10.2	5.84	4.03	9.65	2.77	(8.48 ± 0.44)	(2.43 ± 0.13)
							4.5	11.4	5.98	4.13	9.90	2.84	(9.53 ± 0.46)	(2.74 ± 0.13)
			1	2.54	1.75×10^{-5}	3.06×10^{-3}	3.5	8.89	6.24×10^{5}	4.30×10^{9}	2.06×10^{-6}	5.91×10^{-9}	$(1.55 \pm 0.06) \times 10^{-6}$	$(4.45 \pm 0.17) \times 10^{-9}$
							4	10.2	---------	---------	[a]2.10	6.02	(1.87 ± 0.27)	(5.36 ± 0.78)
							4.5	11.4	6.44	4.44	2.13	6.11	(1.86 ± 0.20)	(5.34 ± 0.57)
		Cantilever, $\theta = 41.5^{\circ}$	0.5	1.27	0.875×10^{-5}	1.53×10^{-3}	---	----	6.02×10^{5}	4.16×10^{9}	9.96×10^{-7}	2.86×10^{-9}	$(9.03 \pm 0.68) \times 10^{-7}$	$(2.60 \pm 0.20) \times 10^{-9}$
			1	2.54	1.75×10^{-5}	3.06×10^{-3}	---	----	5.63	3.88	1.86×10^{-6}	5.34	$(2.11 \pm 0.23) \times 10^{-6}$	(6.05 ± 0.66)
		Cantilever, θ variable	0.5	1.27	0.875×10^{-5}	1.53×10^{-3}	---	----	6.90×10^{5}	4.76	1.14×10^{-6}	3.27×10^{-9}	[b]$(1.12 \pm 0.39) \times 10^{-6}$	$(3.22 \pm 1.12 \times 10^{-9}$
0.001	0.00254	Heart loop	0.5	1.27	2.34×10^{-5}	4.10×10^{-3}	7	17.8	6.09×10^{5}	4.20×10^{9}	3.18×10^{-5}	9.12×10^{-8}	$(1.72 \pm 0.04) \times 10^{-5}$	$(4.94 \pm 0.12) \times 10^{-8}$
							8	20.3	5.96	4.11	3.12	8.95	(1.82 ± 0.04)	(5.22 ± 0.12)
							9	22.9	5.99	4.13	3.14	9.01	(1.98 ± 0.06)	(5.68 ± 0.17)
			1	2.54	4.79×10^{-5}	8.39×10^{-3}	7	17.8	5.60×10^{5}	3.86×10^{9}	5.78×10^{-5}	1.66×10^{-7}	$(3.34 \pm 0.11) \times 10^{-5}$	$(9.59 \pm 0.32) \times 10^{-8}$
							8	20.3	5.35	3.69	5.61	1.61	(3.40 ± 0.02)	(9.75 ± 0.06)
							9	22.9	5.71	3.94	5.99	1.72	(3.83 ± 0.17)	$(1.10 \pm 0.05) \times 10^{-7}$
Aluminum foil														
0.00018	0.00046	Cantilever, $\theta = 41.5^{\circ}$	0.5	1.27	9.36×10^{-6}	1.64×10^{-3}	---	----	[c]6.24×10^{6}	4.30×10^{10}	3.79×10^{-6}	1.09×10^{-8}	$(2.22 \pm 0.20) \times 10^{-6}$	$(6.39 \pm 0.57) \times 10^{-9}$
			1	2.54	1.93×10^{-5}	3.38×10^{-3}	---	----	[c]5.36	3.70	7.47	2.14	(7.26 ± 0.91)	$(2.09 \pm 0.26) \times 10^{-8}$
		Cantilever, θ variable	0.5	1.27	9.36×10^{-6}	1.64×10^{-3}	---	----	[c]7.90×10^{6}	5.45×10^{10}	3.79×10^{-6}	1.09×10^{-8}	(4.71 ± 0.08)	$(1.35 \pm 0.02) \times 10^{-8}$

[a]Young's modulus assumed to be 6.34×10^{5} lbf/in^2 (4.37×10^{9} N/m^2).
[b]Average of 12 tests.
[c]Value too low so that 10^{7} lbf/in^2 (6.9×10^{10} N/m^2) was used in calculating the flexural rigidity.

TABLE V.- FLEXURAL RIGIDITY OF ECHO I MATERIAL

Nominal thickness, t		Test method	Strip width, b		Weight of strip per unit length, w		Strip length, l		Young's modulus, E		Flexural rigidity, D			
											Calculated		Measured	
in.	cm		in.	cm	lbf/in.	N/m	in.	cm	lbf/in^2	N/m^2	lbf-in^2	N-m^2	lbf-in^2	N-m^2
0.0005	0.00127	Heart loop[a]	0.5	1.27	1.23×10^{-5}	2.15×10^{-3}	4	10.2	7.26×10^{5}	5.01×10^{9}	3.00×10^{-6}	8.61×10^{-9}	$(2.21 \pm 0.11) \times 10^{-6}$	$(6.34 \pm 0.32) \times 10^{-9}$
							5	12.7	6.63	4.57	2.74	7.86	(2.56 ± 0.04)	(7.35 ± 0.12)
							5.5	14.0	7.14	4.93	2.94	8.44	(3.00 ± 0.09)	(8.61 ± 0.26)
			1	2.54	2.45×10^{-5}	4.29×10^{-3}	4	10.2	6.26×10^{5}	4.33×10^{9}	5.16×10^{-6}	1.49×10^{-8}	$(4.05 \pm 0.21) \times 10^{-6}$	$(1.16 \pm 0.06) \times 10^{-8}$
							5	12.7	5.53	3.82	4.56	1.31	(4.97 ± 0.01)	(1.43 ± 0.00)
							5.5	14.0	6.73	4.64	5.55	1.60	(5.28 ± 0.22)	(1.52 ± 0.06)
		Heart loop[b]	0.5	1.27	1.23×10^{-5}	2.15×10^{-3}	4	10.2	6.74×10^{5}	4.64×10^{9}	2.78×10^{-6}	7.97×10^{-9}	$(2.27 \pm 0.52) \times 10^{-6}$	$(6.51 \pm 1.44) \times 10^{-9}$
							5	12.7	7.14	4.93	2.94	8.44	(2.74 ± 0.10)	(7.86 ± 0.28)
							5.5	14.0	6.81	4.70	2.81	8.06	(2.87 ± 0.49)	(8.24 ± 1.49)
			1	2.54	2.45×10^{-5}	4.29×10^{-3}	4	10.2	6.20×10^{5}	4.28×10^{9}	5.10×10^{-6}	1.47×10^{-8}	$(4.07 \pm 0.16) \times 10^{-6}$	$(1.17 \pm 0.05) \times 10^{-8}$
							5	12.7	---------	---------	[c]5.09	1.46	(5.74 ± 0.70)	(1.65 ± 0.20)
							5.5	14.0	6.18	4.26	5.08	1.46	(5.44 ± 0.17)	(1.56 ± 0.05)
		Cantilever, $\theta = 41.5^{\circ}$ [a]	0.5	1.27	1.23×10^{-5}	2.15×10^{-3}	---	---	6.86×10^{5}	4.74×10^{9}	2.84×10^{-6}	8.15×10^{-9}	$(7.17 \pm 0.47) \times 10^{-6}$	$(2.06 \pm 0.14) \times 10^{-8}$
			1	2.54	2.45×10^{-5}	4.29×10^{-3}	---	---	6.64×10^{5}	4.58×10^{9}	5.46×10^{-6}	1.57×10^{-8}	$(1.30 \pm 0.10) \times 10^{-5}$	$(3.73 \pm 0.29) \times 10^{-8}$
		Cantilever, $\theta = 41.5^{\circ}$ [b]	0.5	1.27	1.23×10^{-5}	2.15×10^{-3}	---	---	6.55×10^{5}	4.52×10^{9}	2.70×10^{-6}	7.75×10^{-9}	$(2.28 \pm 0.13) \times 10^{-6}$	$(6.54 \pm 0.27) \times 10^{-9}$
			1	2.54	2.45×10^{-5}	4.29×10^{-3}	---	---	6.51×10^{5}	4.50×10^{9}	5.37×10^{-6}	1.55×10^{-8}	$(4.86 \pm 0.34) \times 10^{-6}$	$(1.40 \pm 0.09) \times 10^{-8}$
		Cantilever, θ variable[b]	0.5	1.27	1.23×10^{-5}	2.15×10^{-3}	---	---	6.60×10^{5}	4.56×10^{9}	2.72×10^{-6}	7.80×10^{-9}	$(2.53 \pm 0.42) \times 10^{-6}$	$(7.26 \pm 1.21) \times 10^{-9}$

[a]Aluminized side of Echo I material in compression.

[b]Aluminized side of Echo I material in tension.

[c]Young's modulus assumed to be 6.19×10^{5} lbf/in^2 (4.27×10^{9} N/m^2).

TABLE VI.- FLEXURAL RIGIDITY OF SPACECRAFT LAMINATES

Laminate	Nominal thickness, t		Deflection angle, θ, deg	Strip width, b		Weight of strip per unit length, w		Extensional stiffness		Flexural rigidity, D	
	in.	cm		in.	cm	lbf/in.	N/m	lbf/in.	N/m	lbf-in^2	N-m^2
Explorer IX laminate	0.0020	0.00508	Variable[a]	0.5	1.27	8.2×10^{-5}	1.44×10^{-2}	4.14×10^3	7.25×10^5	$(2.28 \pm 0.47) \times 10^{-3}$	$(6.54 \pm 1.35) \times 10^{-6}$
Echo II laminate	0.00071	0.00181	41.5	0.5	1.27	2.8×10^{-5}	5.0×10^{-3}	2.18×10^3	3.82×10^5	$(1.41 \pm 0.18) \times 10^{-4}$	$(4.05 \pm 0.52) \times 10^{-7}$
			41.5	1	2.54	5.70	10.0	2.30	4.03	(2.79 ± 0.31)	(8.00 ± 0.92)
			Variable	0.5	1.27	2.85	5.0	2.18	3.82	[b](2.92 ± 0.66)	(8.38 ± 1.90)
X-32B laminate	0.0010	0.00254	41.5	1	2.54	3.82×10^{-5}	6.69×10^{-3}	2.87×10^2	5.03×10^4	$(2.14 \pm 0.06) \times 10^{-4}$	$(6.14 \pm 0.17) \times 10^{-7}$
			Variable	0.5	1.27	1.91	3.35	2.85	5.00	(1.21 ± 0.54)	(3.47 ± 1.55)
A/M/A laminate	0.00270	0.00685	Variable	0.5	1.27	8.9×10^{-5}	1.56×10^{-2}	5.93×10^3	1.04×10^6	$(2.50 \pm 1.06) \times 10^{-3}$	$(7.17 \pm 3.04) \times 10^{-6}$

[a]Aluminum side in tension.
[b]Average of 70 tests.

TABLE VII.- FLEXURAL RIGIDITY OF 0.5-INCH-WIDE (1.27-CM) STRIPS OF ECHO II LAMINATE

Apparatus	Flexural rigidity, D			
	Variable-angle technique		Fixed-angle technique	
	lbf-in^2	N-m^2	lbf-in^2	N-m^2
Variable angle, fig. 4(a)	$(2.16 \pm 0.8) \times 10^{-4}$	$(6.20 \pm 2.30) \times 10^{-7}$	$(1.93 \pm 0.4) \times 10^{-4}$	$(5.54 \pm 1.15) \times 10^{-7}$
Fixed angle, fig. 4(b)	$(2.20 \pm 0.6) \times 10^{-4}$	$(6.31 \pm 1.72) \times 10^{-7}$	$(1.89 \pm 0.4) \times 10^{-4}$	$(5.42 \pm 1.15) \times 10^{-7}$

TABLE VIII.- WEIGHT EFFICIENCY OF THIN FILMS AND COMPOSITE MATERIALS RELATIVE TO ECHO I MATERIAL

Material	D		D/W		Weight efficiency relative to Echo I material
	lbf-in^2	N-m^2	in^4	cm^4	
0.00035-in.-thick (0.00089 cm) PET film	1.9×10^{-6}	5.5×10^{-9}	0.109	4.54	0.545
0.001-in.-thick (0.00254 cm) PET film	3.5×10^{-5}	1.0×10^{-7}	0.731	30.4	3.66
0.00018-in.-thick (0.00046 cm) aluminum foil	7.3×10^{-6}	2.1×10^{-8}	0.378	15.7	1.89
Echo I material	4.9×10^{-6}	1.4×10^{-8}	0.200	8.32	1.00
Echo II laminate	2.8×10^{-4}	8.0×10^{-7}	4.91	204	24.6
Explorer IX laminate	4.6×10^{-3}	1.3×10^{-5}	28.1	1170	141
X-32B laminate	2.1×10^{-4}	6.0×10^{-7}	5.50	229	27.5
A/M/A laminate	5.0×10^{-3}	1.4×10^{-5}	28.1	1170	141

TABLE IX.- FLEXURAL RIGIDITY OF THIN FILMS AND COMPOSITE MATERIALS AS DETERMINED BY THE ELASTICA METHOD AND BY A COMMERCIAL STIFFNESS TESTER

Material	Flexural rigidity, D		Deflection force	
	lbf-in^2	N-m^2	lbf	N
0.00035-in.-thick (0.00089 cm) PET film	1.9×10^{-6}	5.5×10^{-9}	6.89×10^{-3}	3.06×10^{-2}
Echo I material	4.9×10^{-6}	1.4×10^{-8}	7.35×10^{-3}	3.27×10^{-2}
0.00018-in.-thick (0.00046 cm) aluminum foil	7.3×10^{-6}	2.1×10^{-8}	6.95×10^{-3}	3.09×10^{-2}
0.0001-in.-thick (0.00254 cm) PET film	3.5×10^{-5}	1.0×10^{-7}	3.96×10^{-2}	1.76×10^{-1}
Echo II laminate	2.8×10^{-4}	8.0×10^{-7}	1.04×10^{-1}	4.62×10^{-1}
Explorer IX laminate	4.6×10^{-3}	1.3×10^{-5}	8.08×10^{-1}	3.59

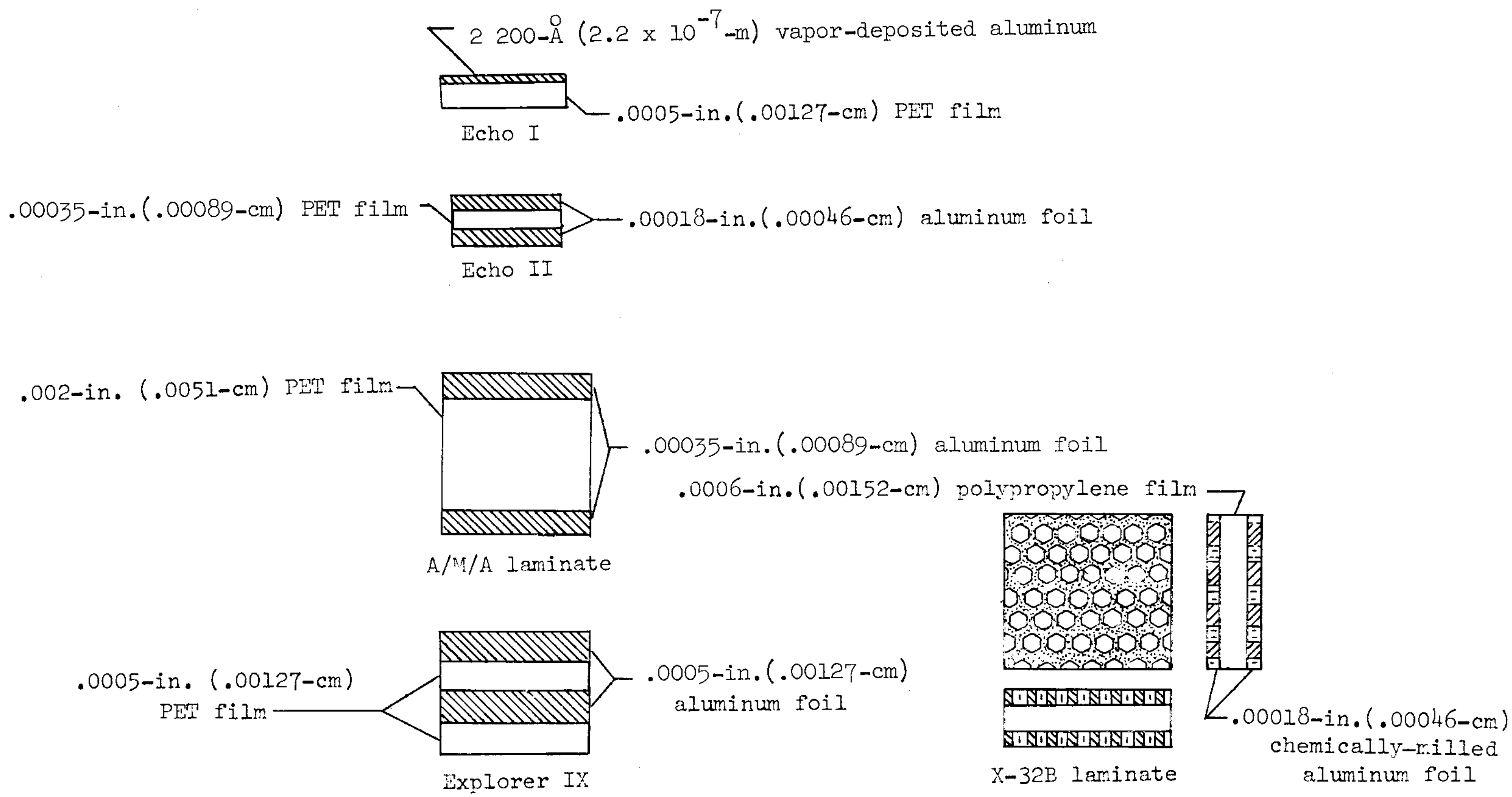
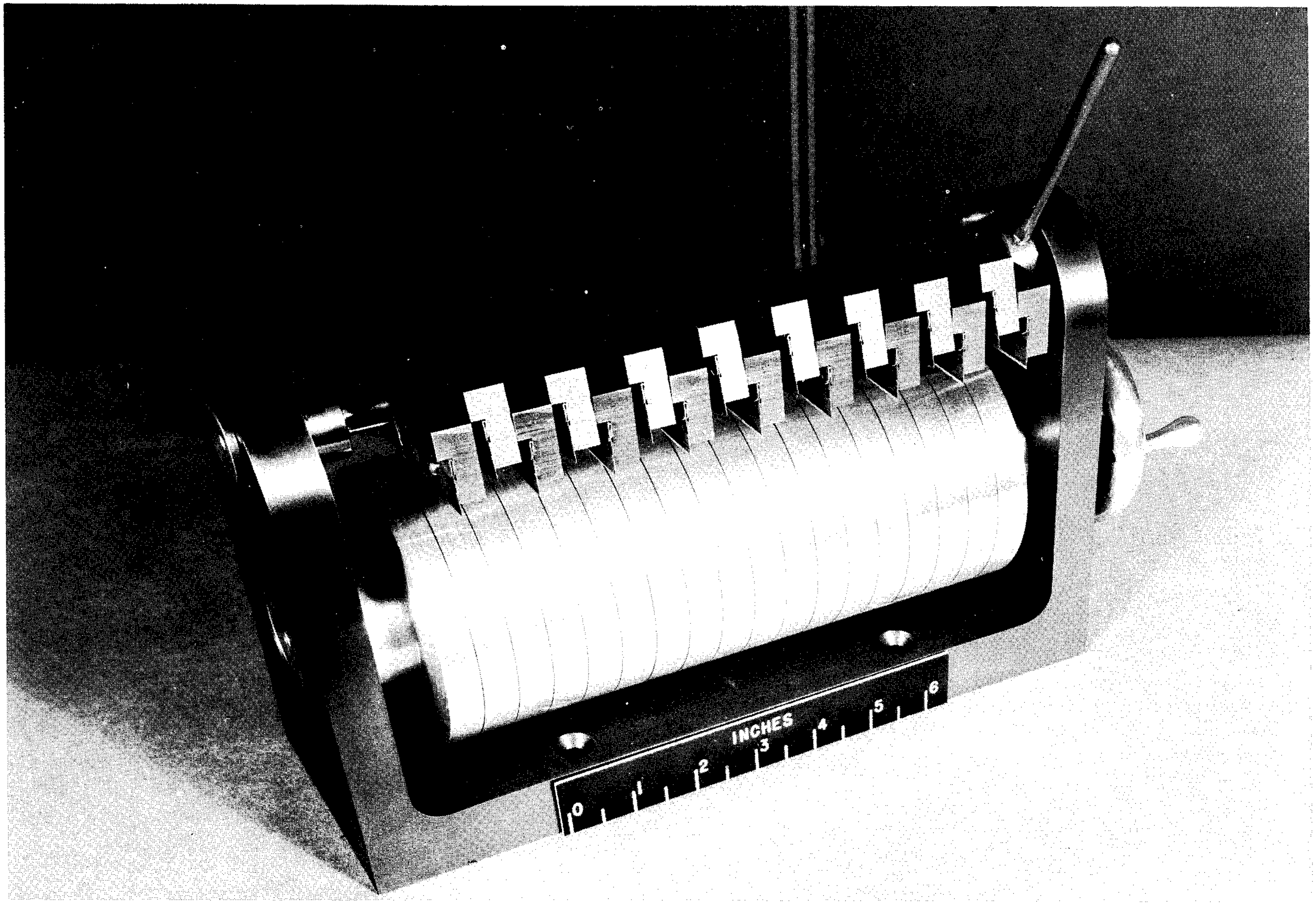


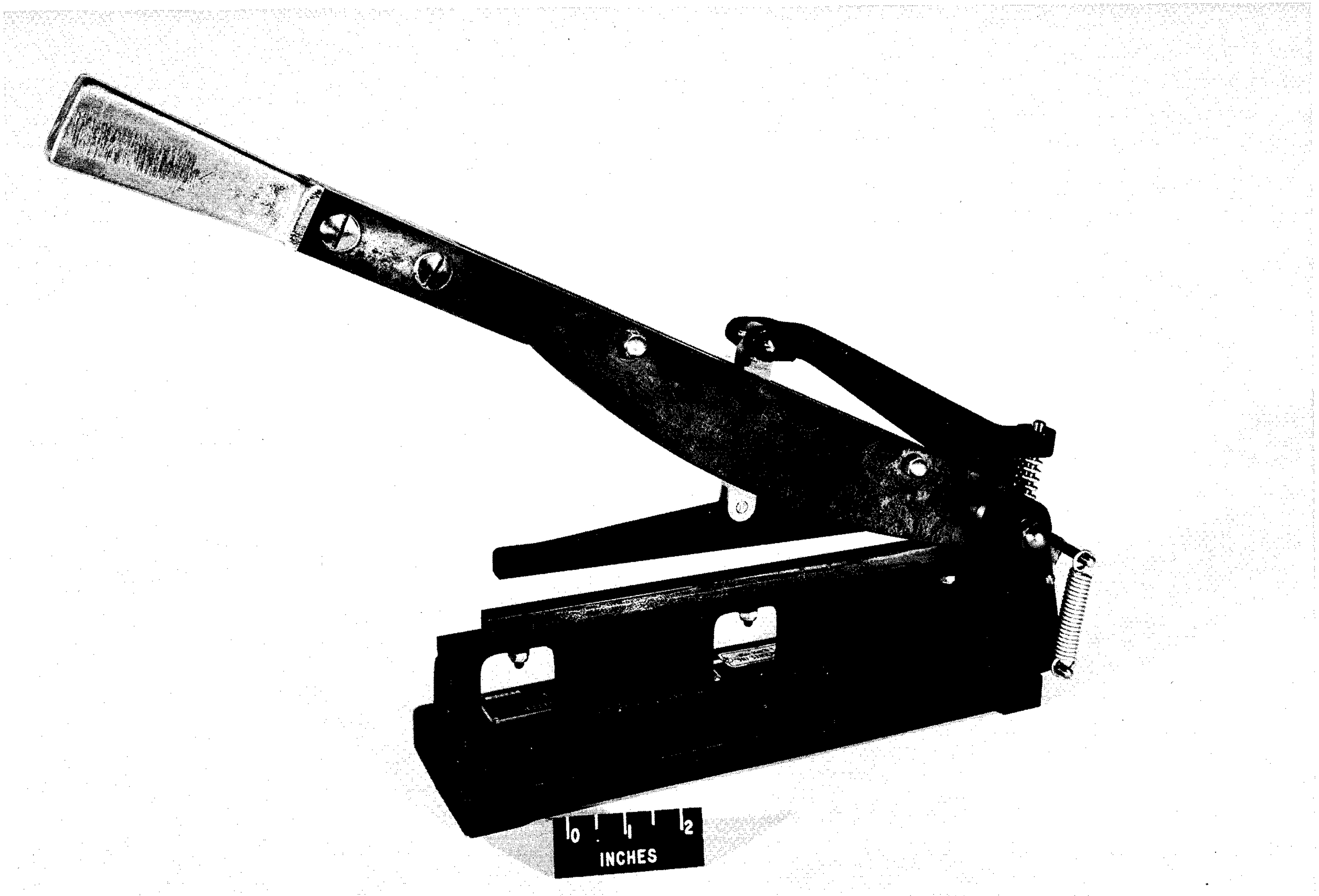
Figure 1.- Cross section of composite materials. All dimensions are nominal.



L-62-5389

(a) Drum cutter for polymer films.

Figure 2.- Specimen cutters.



(b) Shear cutter for foil and laminates. L-65-2154

Figure 2.- Concluded.

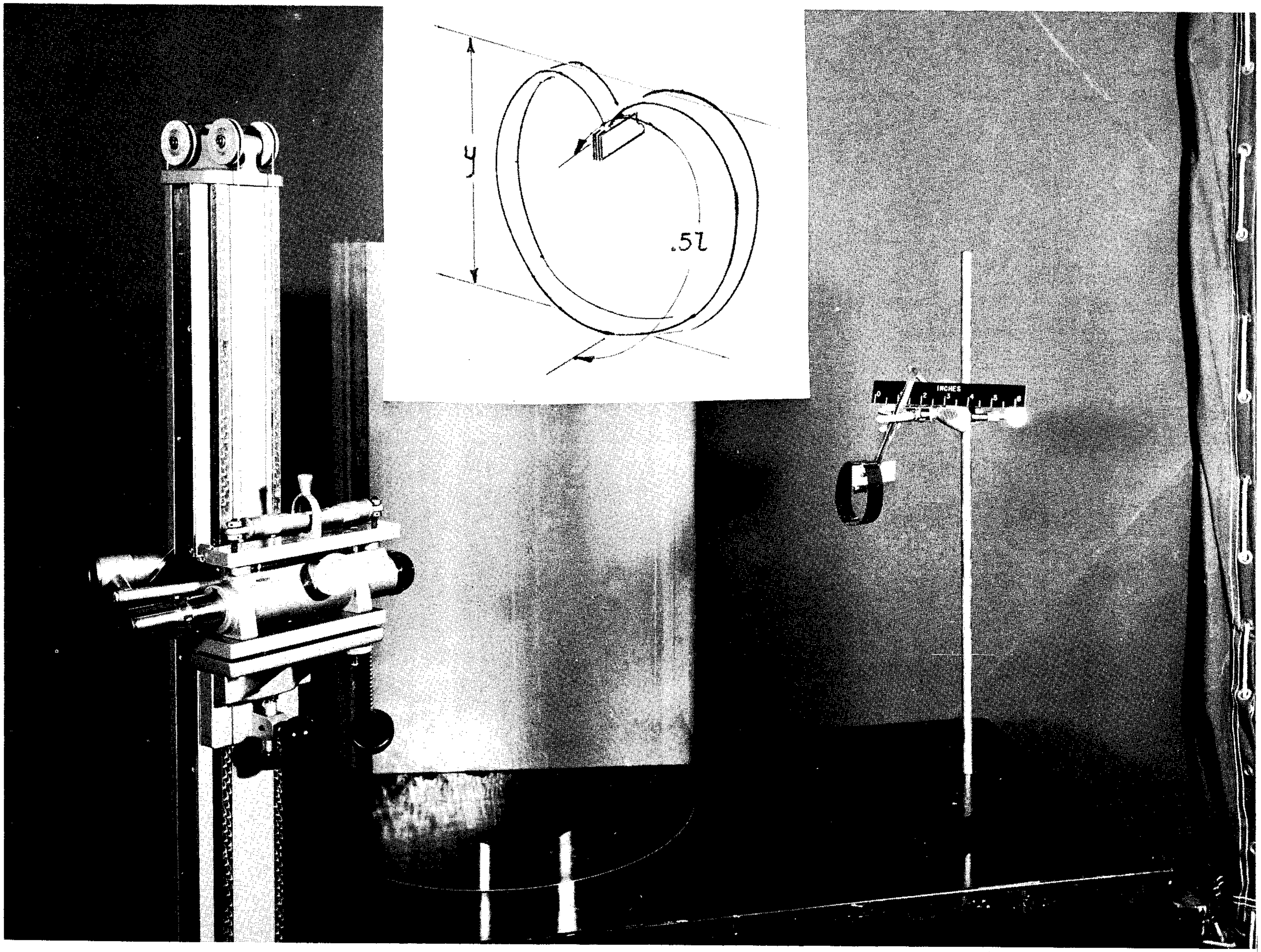
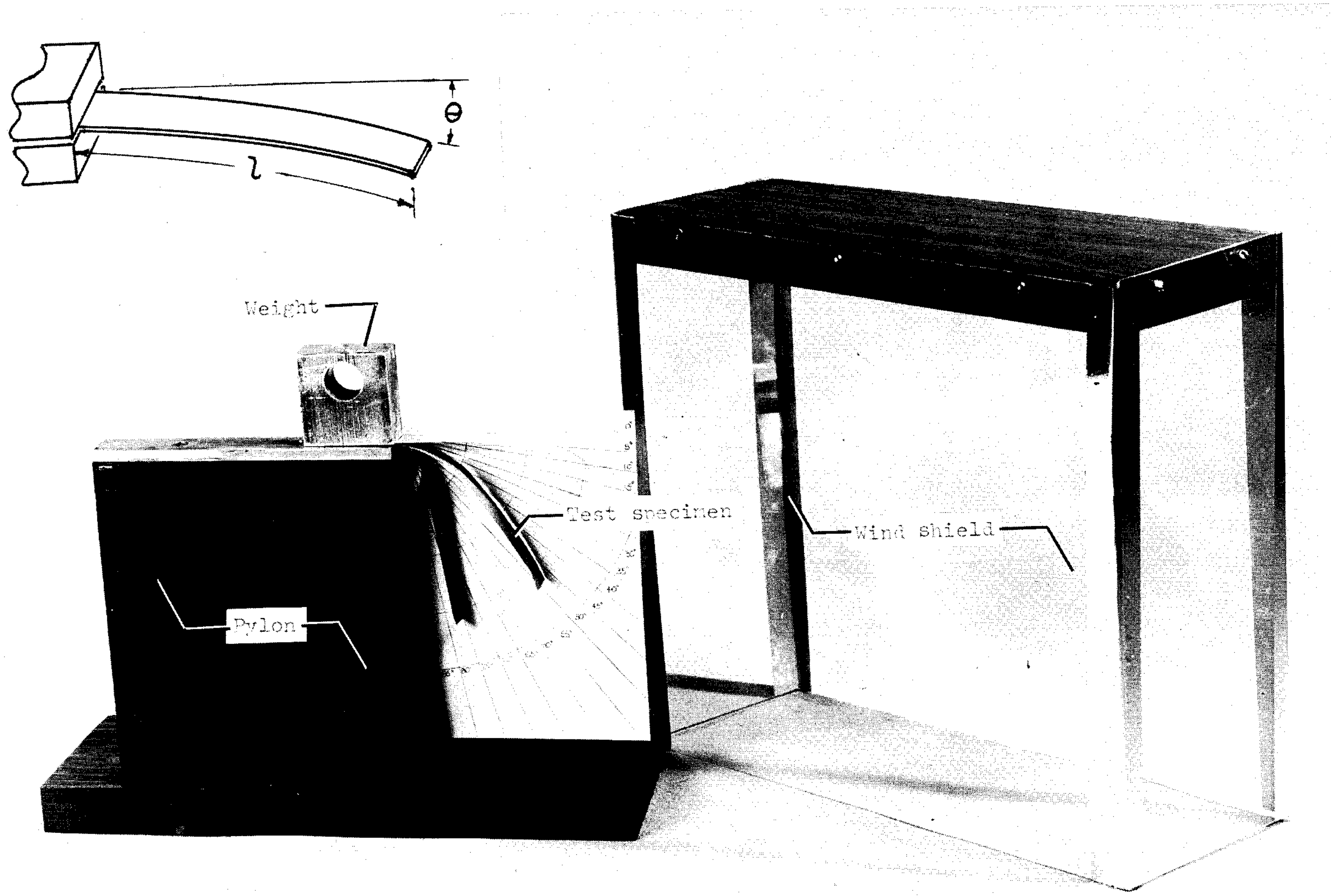


Figure 3.- Heart-loop apparatus.

L-62-5390.1



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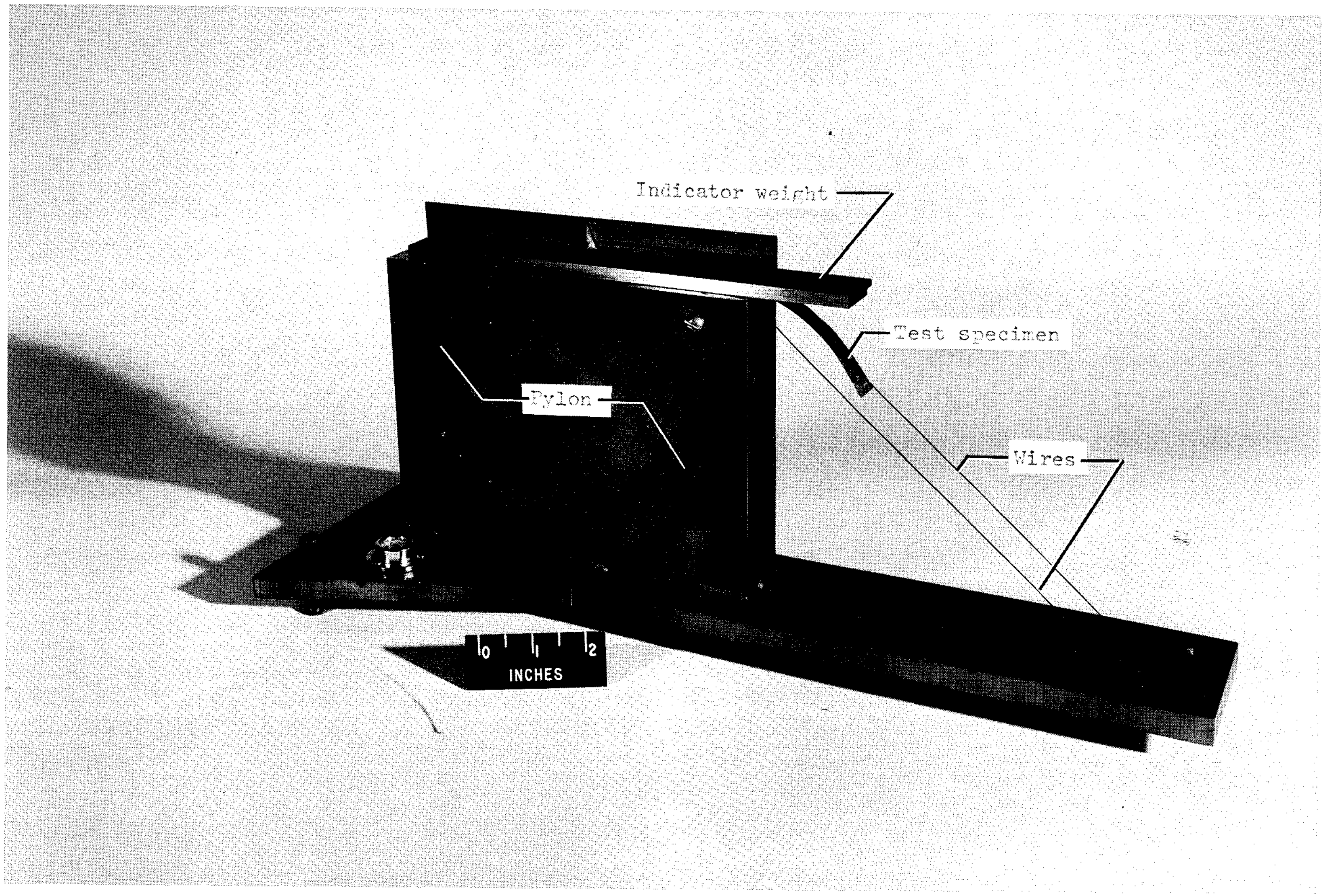
(a) Variable angle.

Figure 4.- Cantilever apparatus.



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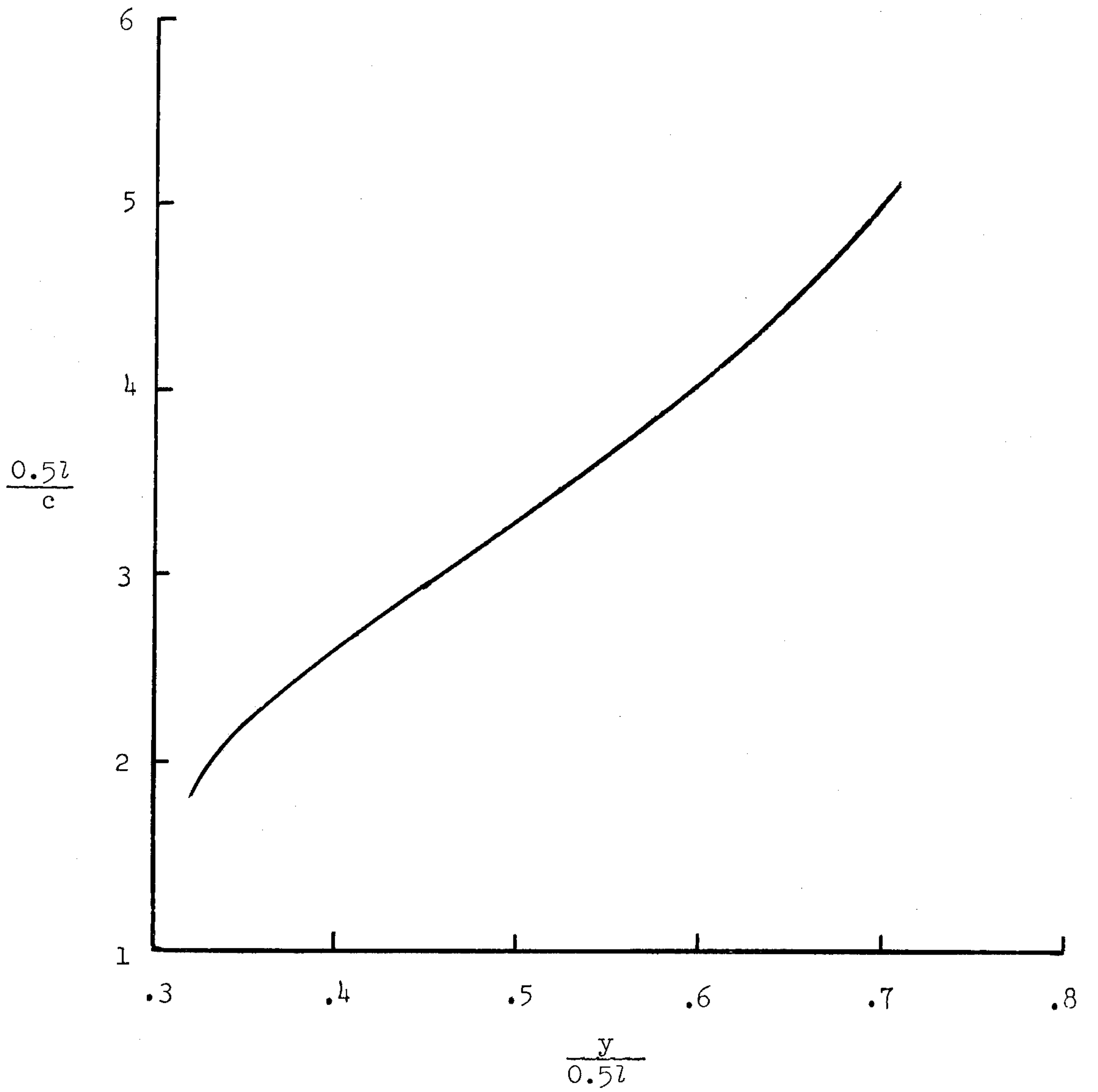
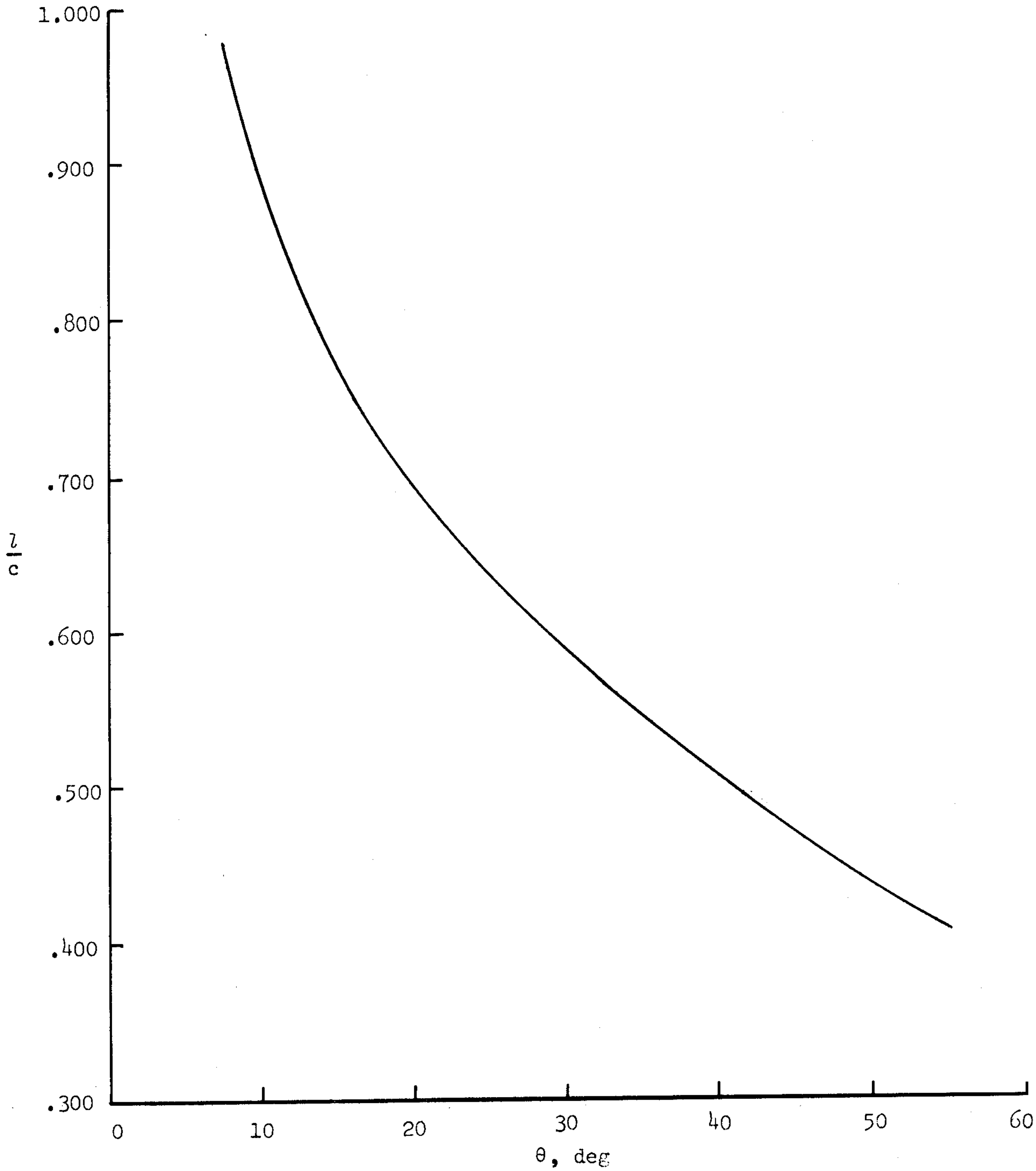
(b) Fixed angle ($\theta = 41.5^{0}$).

Figure 4.- Concluded.



(a) Relationship between ratio of strip deflection y to one-half strip length $0.5l$ and ratio of one-half strip length $0.5l$ to bending length c. Heart-loop method.

Figure 5.- Relationships of rigidity characteristics of thin materials. (The curves were taken from ref. 15.)



(b) Relationship between strip deflection angle θ and ratio of bending length c to strip length l. Cantilever method.

Figure 5.- Concluded.

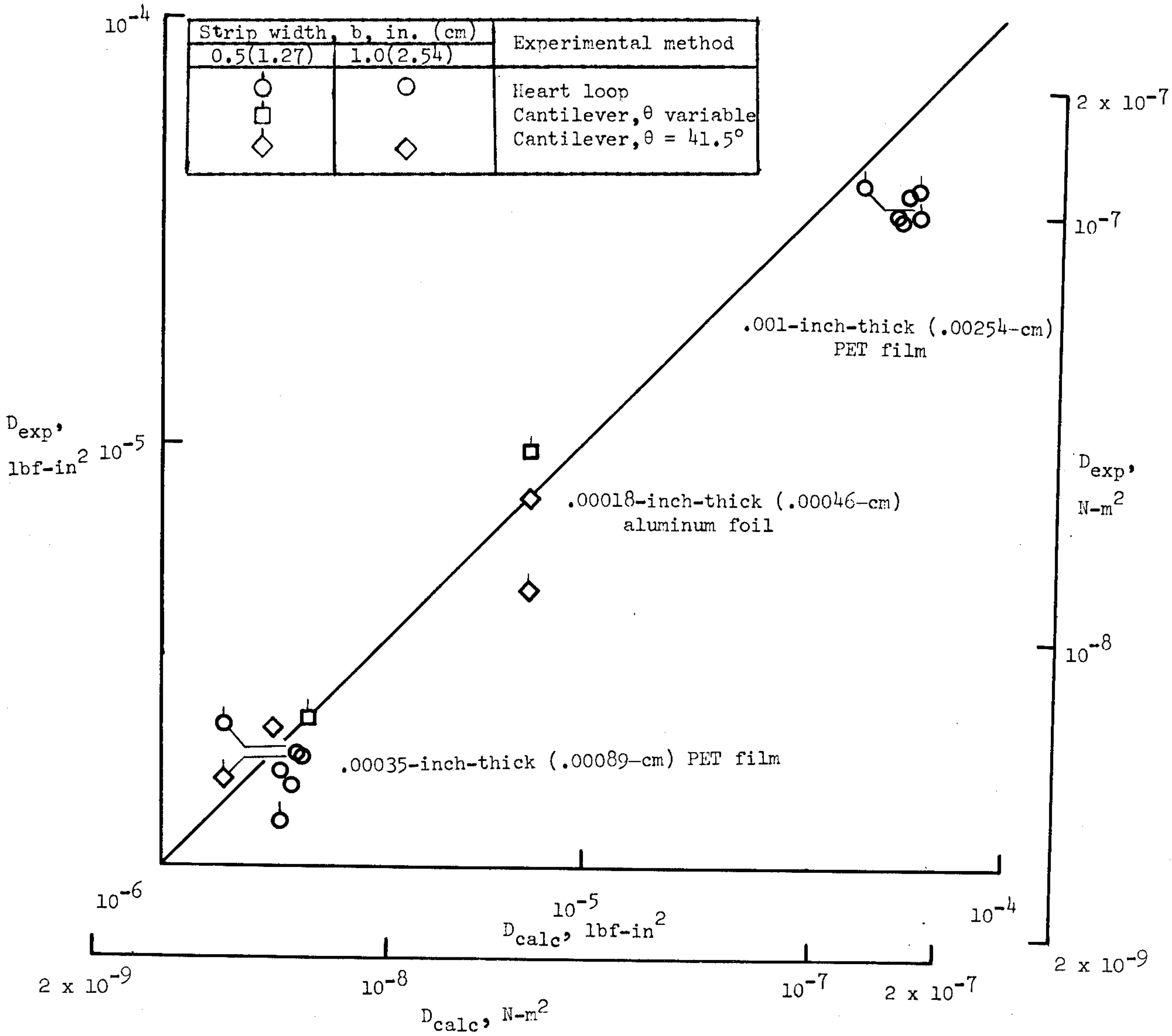


Figure 6.- Comparison of calculated and measured rigidity of PET film and aluminum foil. All 0.5-in. (1.27-cm) values were normalized to unit width when plotted.

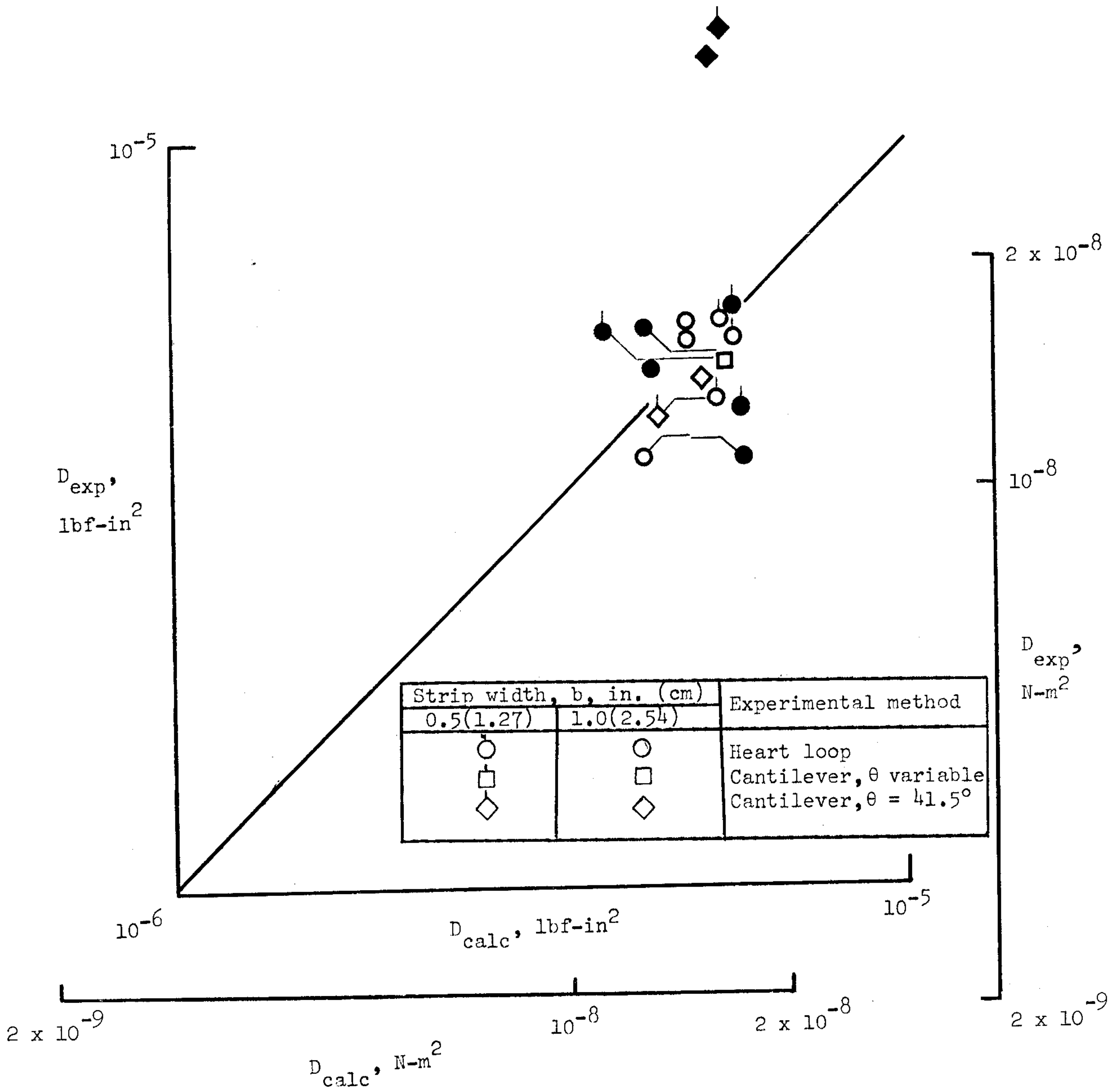


Figure 7.- Comparison of calculated and measured rigidity of Echo I material. All 0.5-in. (1.27-cm) values were normalized to unit width when plotted. Closed symbols denote aluminum in compression.

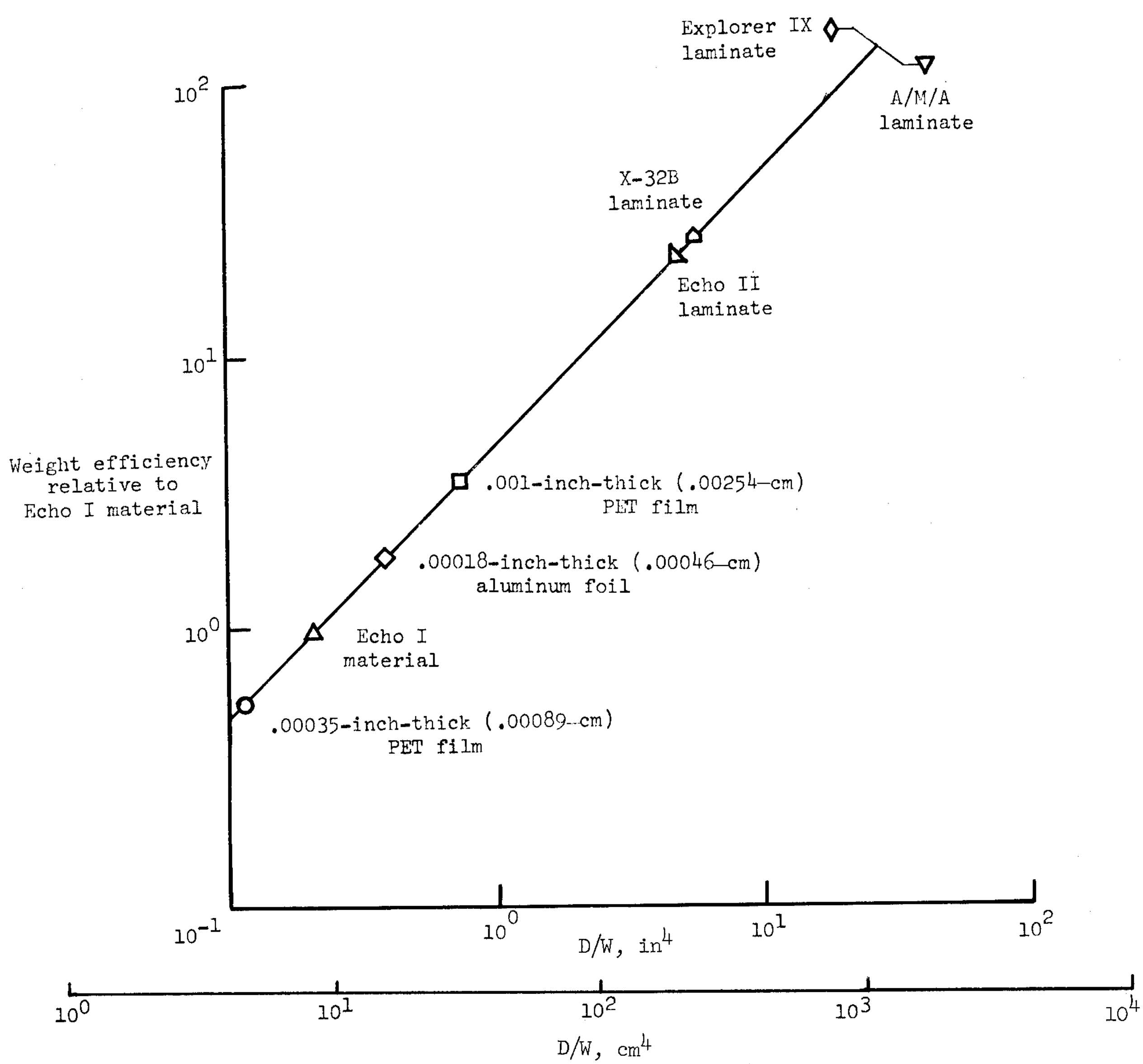


Figure 8.- Weight efficiency of thin films and laminates relative to that of Echo I.

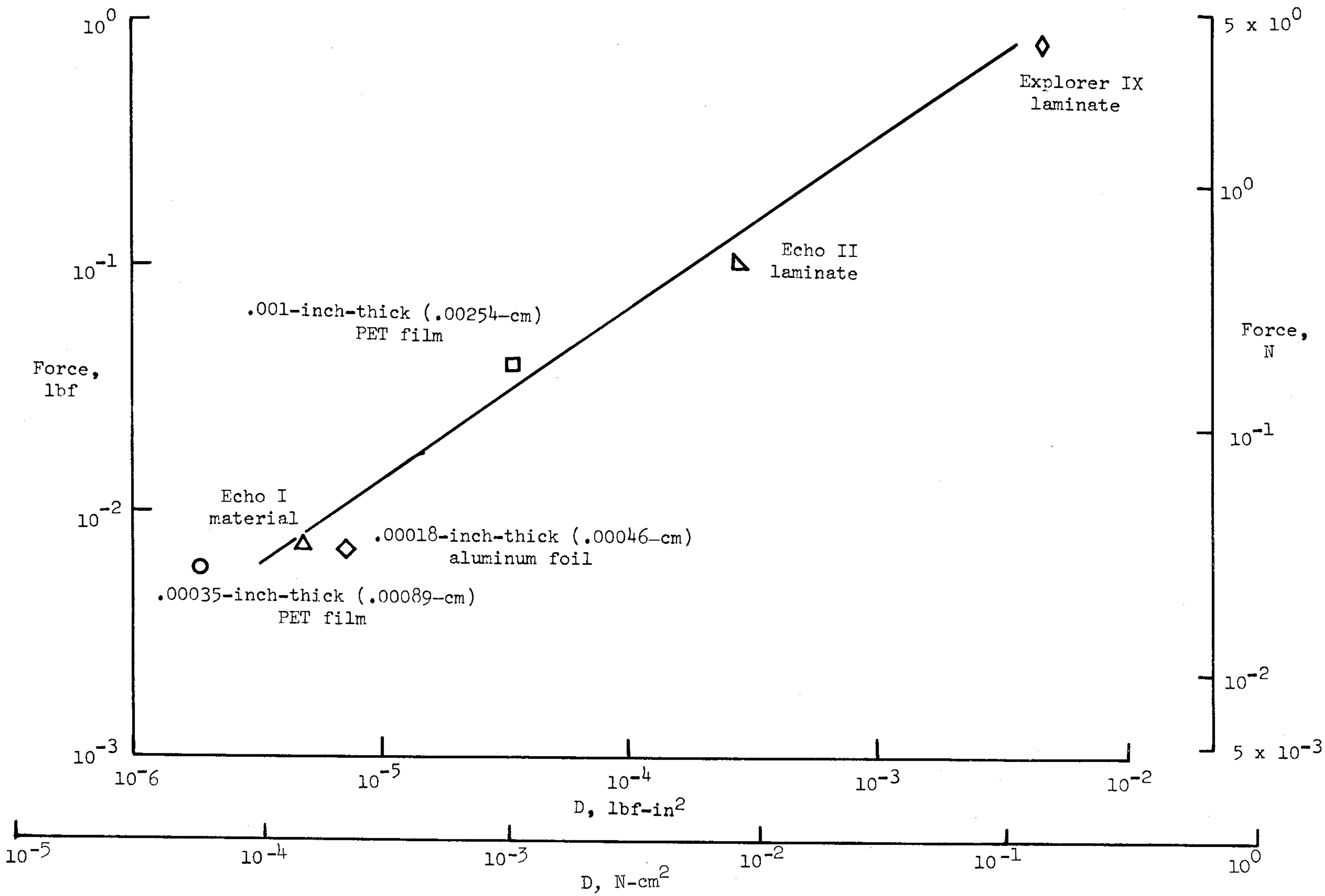


Figure 9.- Correlation between flexural rigidity as determined by the elastica method and by a commercial stiffness tester.

NASA-Langley, 1966 L-4257

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